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Estimating Source Terms For Diverse Spent Nuclear Fuel Types

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Abstract – *The U.S. Department of Energy (DOE) National Spent Nuclear Fuel Program is responsible for developing a defensible methodology for determining the radionuclide inventory for the DOE spent nuclear fuel (SNF) to be dispositioned at the proposed Monitored Geologic Repository at the Yucca Mountain Site. SNF owned by DOE includes diverse fuels from various experimental, research, and production reactors. These fuels currently reside at several DOE sites, universities, and foreign research reactor sites. Safe storage, transportation, and ultimate disposal of these fuels will require radiological source terms as inputs to safety analyses that support design and licensing of the necessary equipment and facilities. This paper summarizes the methodology developed for estimating radionuclide inventories associated with DOE-owned SNF. The results will support development of design and administrative controls to manage radiological risks and may later be used to demonstrate conformance with repository acceptance criteria.*

I. INTRODUCTION

The U.S. Department of Energy (DOE) has operated and sponsored a variety of research, test, and other experimental reactors. To support nuclear nonproliferation objectives, DOE has also taken custody of many foreign research reactor (FRR) fuels of U.S. origin. These DOE and foreign research reactors represent a wide range of reactor types and include unique design features such as core configuration, fuel element and assembly geometry, reflector and coolant materials, operational characteristics, and neutron spatial and spectral properties.

DOE is presently responsible for storage and final disposition of spent nuclear fuel (SNF) that spans several decades of nuclear research and defense-related material production. Throughout much of this period, data were not created or maintained in accordance with current Office of Civilian Radioactive Waste Management requirements. Historical data such as fuel fabrication, operations, and storage records are incomplete or questionable for many of these fuels. Although these fuels have been safely stored and handled for many years, the safety analyses is often based on source terms that have been estimated or bounded using a variety of techniques. For many DOE SNFs, adequate fuel-specific source term data and documentation are not readily available to support repository analyses or to demonstrate compliance with repository acceptance criteria.

Obtaining the SNF radionuclide inventories by direct characterization would be very costly and could not be completed in a timeframe to support repository design and licensing schedules. Hence, initial efforts focused on calculating radionuclide inventories for each SNF using ORIGEN-based techniques. However, because of the limited availability of input data, these calculations required a substantial research and calculational effort. Further, their accuracy was difficult to establish for many DOE SNFs because the results inherit the uncertainty of the inputs and because of the limited availability of postirradiation examination data for use in validation.

A more effective method for consistently and defensibly determining the radionuclide inventories of DOE SNF was needed.

II. APPROACH

Preliminary dose calculations and scoping studies indicate that repository performance is relatively insensitive to the form and composition of DOE SNFs. [1] [2] The three primary reasons for this are 1) DOE SNFs comprise a relatively small fraction (~3% by MTHM) of the total SNF that will be placed in the repository; 2) DOE SNFs are primarily from research, test, and production reactors that are typically low burnup fuels and are thus less likely to have high concentrations of radionuclides; and 3) DOE SNF canisters will maintain confinement during credible preclosure event sequences. [3] Because Monitored Geologic Repository (MGR) safety analyses can accommodate considerable uncertainty in the radionuclide inventories of DOE SNFs, conservative estimates are considered sufficient to support design and licensing as well as for eventual certification of the SNFs for disposal.

The National Spent Nuclear Fuel Program (NSNFP) chartered a team to develop a methodology that could be consistently applied to estimate the radionuclide inventories for the broad range of SNF in DOE custody. The team included representatives from each DOE SNF storage site, Argonne National Laboratory, and the proposed MGR. A methodology was developed for obtaining conservative and reasonable source term estimates for all DOE SNFs using available information and, when necessary, conservative assumptions. The process, referred to as the template methodology, relies on existing ORIGEN results that provide radionuclide inventories for typical SNF at a range of decay times. These results are used as templates for estimating radionuclide inventories for other similar fuels by scaling them to account for differences in burnup and fuel mass. A similar approach has been employed on a more limited scale to estimate radionuclide inventories needed to support shipment and acceptance of FRRs. [4]

III. METHODOLOGY

To estimate an SNF source term, an appropriate template is selected to model the production of radionuclides. Radionuclide inventories are extracted from the template for the desired decay period and then scaled to account for differences in fuel mass and specific burnup.

The template is selected based on four parameters that play a key role in establishing the neutron energy spectrum within the core. The four parameters are: 1) the reactor moderator, 2) the fuel cladding, 3) fuel enrichment, and 4) the fuel beginning-of-life (BOL) heavy metal constituents. These four parameters strongly influence activation and transmutation. They are known for most DOE SNFs and, when not known, can be conservatively estimated.

The reactor moderator is the key influence on neutron thermalization, absorption, and lifetime. Knowledge of the moderator type also narrows the field of potential fuel types. The reactor fuel type (cladding, enrichment, and BOL heavy metal constituents) also affects the neutron spectral properties within the reactor as well as its response to the neutron spectrum. The initial enrichment and heavy metal content of the fuel are key influences on the production and destruction rates of actinides. Cladding materials affect production of activation products.

The template methodology assumes that first order spectral effects will be reasonably represented by the reactor core and neutron cross sections modeled for the selected template fuel. The spectral and spatial differences due to structural materials, plate or rod pitch, fuel meat and clad thickness, burnable poison, etc. are expected to be relatively small and of secondary importance.

Although radionuclide buildup and depletion are not true linear functions of time or burnup, they are modeled linearly in the template methodology. Error is introduced to the extent that the scaling accounts for differences between the template's and the fuel's specific burnups (i.e., burnup per unit mass). The error that may be introduced varies for each radionuclide and is determined by the slope and curvature of the rate of buildup of the radionuclide at the burnup modeled in the template and also by the magnitude and direction of the burnup multiplier (ratio of the specific burnup of the fuel being estimated over the specific burnup of the template fuel). As illustrated in Figure 1, if the rate of buildup of a radionuclide is positive and increasing with burnup at the template burnup value (burnup multiplier of 1.0), an estimate using a burnup multiplier with a value of less than one would overpredict the actual radionuclide inventory while an estimate with a multiplier greater than one would underpredict its actual value.

As a result, the effect of scaling on uncertainty may vary for each radionuclide and for each fuel and thus cannot be quantified in any generalized way. However, analysis of the data summarized in Reference 5 yielded two observations. First, representing radionuclides as a linear function of burnup reasonably models radionuclide production over a broad range of burnups. Second, for most radionuclides, the nonlinearity of the buildup rate with respect to burnup is both positive and increasing (i.e., slope and curvature are positive).

The template methodology produces radionuclide inventory estimates based on matching reactor moderator type and fuel clad, enrichment, and BOL heavy metal constituents with a template and then linearly scaling the template results to account for burnup. Conservative assumptions with respect to these parameters provides confidence that the methodology will yield conservative results.

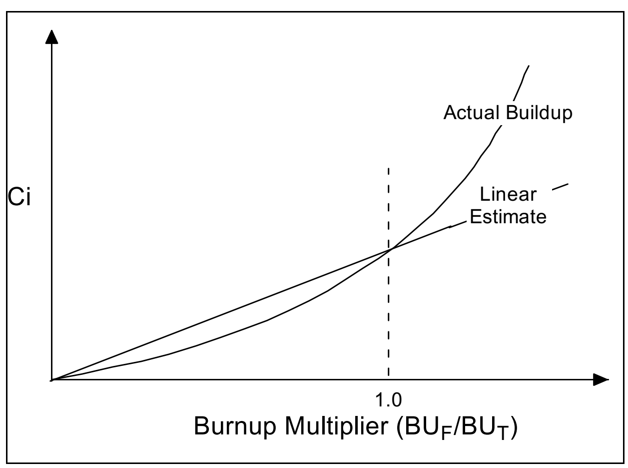

Fig. 1. Effect of linear scaling.

IV. IMPLEMENTATION

Implementation of the template methodology requires preparation of templates to represent the range of SNFs to be estimated. For each SNF, an appropriate template is selected to model the generation of radionuclides. The template results representing the desired decay time are then selected and scaled to account for differences in burnup between the template fuel and the fuel whose radiological inventories are being estimated.

IV.A. Generating Templates

By modeling various combinations of reactor moderator, fuel enrichment, fuel compound, and fuel cladding; templates have been developed to reasonably model a broad range of DOE SNF. These templates provide radionuclide inventories at 10 different decay periods ranging from 5 to 100 years following irradiation. Template results include 145 radionuclides that typically account for over 99.9% of the total curie inventory.

In order to establish the total number of templates needed to encompass the DOE spent fuel inventory, DOE SNFs were grouped based on attributes important to predicting radionuclide production (i.e., the four template selection parameters). Similar approaches have been successfully employed for grouping DOE SNFs to simplify other repository analyses. [6]

When selecting the template fuel to represent each group, consideration was given to the relative quantities of the fuels within the group as well as to the availability of existing depletion calculations and/or input and validation data to support the calculations. Templates were generated using ORIGEN-based calculational techniques described in Reference 7, which includes discussion and references to relevant experimental data and validation studies.

To address fuels that did not fit within one of the identified groups, a hypothetical template was developed with the intention of bounding the radionuclide inventories for virtually any conceivable SNF. It was produced by using ORIGEN to model a hypothetical fuel with properties intended to maximize the production of actinides and activation products. The burnup of the hypothetical template fuel was adjusted to maximize the curies per MWd for key radionuclides. To further ensure conservatism, each resulting radionuclide inventory was normalized to a per MWd/kg basis and compared to the corresponding normalized value from each of the other templates. The highest of these normalized values was retained for each radionuclide. The resulting template is referred to as the Worst Case Template. It contains, for each radionuclide at each of the 10 decay periods, a normalized curie content equal to the highest of all the template fuels, including the hypothetical template fuel.

Results were calculated for fifteen template fuels. Table 1 shows the template selection parameters for the fifteen templates. These templates are sufficient to address 99.9% (by heavy metal mass) of the DOE SNF. The Worst Case Template was employed to conservatively estimate source terms for the remaining DOE SNFs. A description of the fifteen template fuels along with the Worst Case Template and their calculated radionuclide inventories is provided in Appendix A of Reference 8.

TABLE 1. Templates

Moderator	Fuel Clad	BOL Enrichment	BOL Heavy Metal Constituents
Fast	Stainless Steel	10 to 30%	Pu and U
Fast	Zirconium	10 to 40%	U
Graphite	Graphite	60 to 100%	Th and U
Graphite	Zirconium	0 to 5%	U
Heavy Water	Aluminum	40 to 100%	U
Heavy Water	Aluminum	10 to 20%	U
Heavy Water	Stainless Steel	0 to 5%	U
Heavy Water	Zirconium	0 to 5%	U
Light Water	Aluminum	60 to 100%	U
Light Water	Stainless Steel	60 to 100%	U
Light Water	Zirconium	60 to 100%	Th and U
Light Water	Zirconium	0 to 5%	U
LW/U-Zrx	Aluminum	10 to 20%	U
LW/U-Zrx	Stainless Steel	60 to 100%	U
LW/U-Zrx	Stainless Steel	10 to 20%	U

IV.B. Selecting a Template

Available information is used to select a template and to obtain nominal and bounding burnups used to scale the template results. An appropriate template is selected for a particular spent fuel based on the reactor moderator, the fuel compound, the fuel cladding, and BOL enrichment. When possible, a template is selected that matches all four parameters. If a parameter is not known, a conservative assumption may be applied as shown in Table 2. If the spent fuel still does not align with any of the available templates, the Worst Case Template may be used.

TABLE 2. Conservative Assumptions for Missing Information

Unknown Parameter	Conservative Assumption	Basis
Cladding	If cladding is unknown, assume it is stainless steel.	Stainless steel is more conducive to the production of activation products than other typical cladding materials (e.g., aluminum, zirconium, graphite).
Fuel compound	If end-of-life (EOL) plutonium exceeds 1% by weight, assume a mixed oxide fuel. If thorium is present at EOL, assume a U-Th oxide fuel. Otherwise, assume a uranium fuel.	The majority of spent nuclear fuels (SNFs) are uranium fuels. Uranium or thorium fuels are assumed only if indicated by EOL radionuclides.
BOL enrichment	Assume the initial fissile mass equals the fissile mass depleted (i.e., 100% depletion). If needed, the initial uranium inventory may be estimated as the EOL heavy metal mass plus the initial fissile mass.	Estimates the lowest possible enrichment (i.e., will underpredict the actual enrichment) and thus maximizes heavy metals available for transmutation. These correlations assume uranium fuels. Uranium fuels compose the majority of DOE SNFs. These correlations also provide reasonable approximations for other fuel types.
Moderator	Heavy water.	Heavy water moderation produces a soft neutron spectrum that is generally more conducive to transmutation of heavy metals.
Reactor shutdown or fuel removal date	Date for fuel shipping, storage, or any other activity that confirms the fuel was no longer in the reactor.	Use of a later date will produce a conservative result for all radionuclides of interest except Neptunium-237 and Americium-241 because, for a period, they may increase rather than decrease with decay time.

IV.C. Accounting for Decay Time

The precalculated template results include radionuclide inventories for 145 radionuclides at each of 10 decay times (5, 10, 15, 20, 25, 35, 50, 65, 80, and 100 years). The decay time used in the estimate is determined by the number of years between the desired date of the estimated source term and the date the SNF irradiation activities ended (i.e., reactor shutdown or fuel removal from the core). For conservatism, the 5-year decay period is selected if no information is available to identify the fuel decay period.

When the desired decay time falls in the interval between two of the precalculated decay times, the higher of the two surrounding inventories is selected for each radionuclide. For example, if the desired decay period is 13 years, the inventory at both the 10 and 15-year decay periods is considered for each radionuclide, and the higher of the two inventories is selected. This provides conservatism even for radionuclides whose inventory may be building up rather than being depleted with time.

IV.D Scaling for Burnup

The estimate is completed by scaling each of the selected template results to adjust for burnup. Scaling is performed using the simple linear relationship:

$$y_i = m_i x + b_i \qquad (1)$$

where

y_i = estimated inventory of radionuclide i (Ci)
m_i = rate of change of radionuclide i with respect to burnup from the template fuel (Ci/MWd)
x = burnup of fuel being estimated (MWd)
b_i = initial inventory of radionuclide i (Ci).

If $m_i < 0$ (i.e., radionuclide inventory decreases with burnup), then b_i is used to conservatively represent the bounding inventory.

Because burnup information is not accurately known for many DOE SNFs, the methodology includes a process for estimating burnup using available information, which in some cases, may consist of no more than the end-of-life (EOL) heavy metal mass. A simplified logic diagram of this process is illustrated in Figure 2. The detailed logic flow diagram is included as Figure 1 of Reference 8.

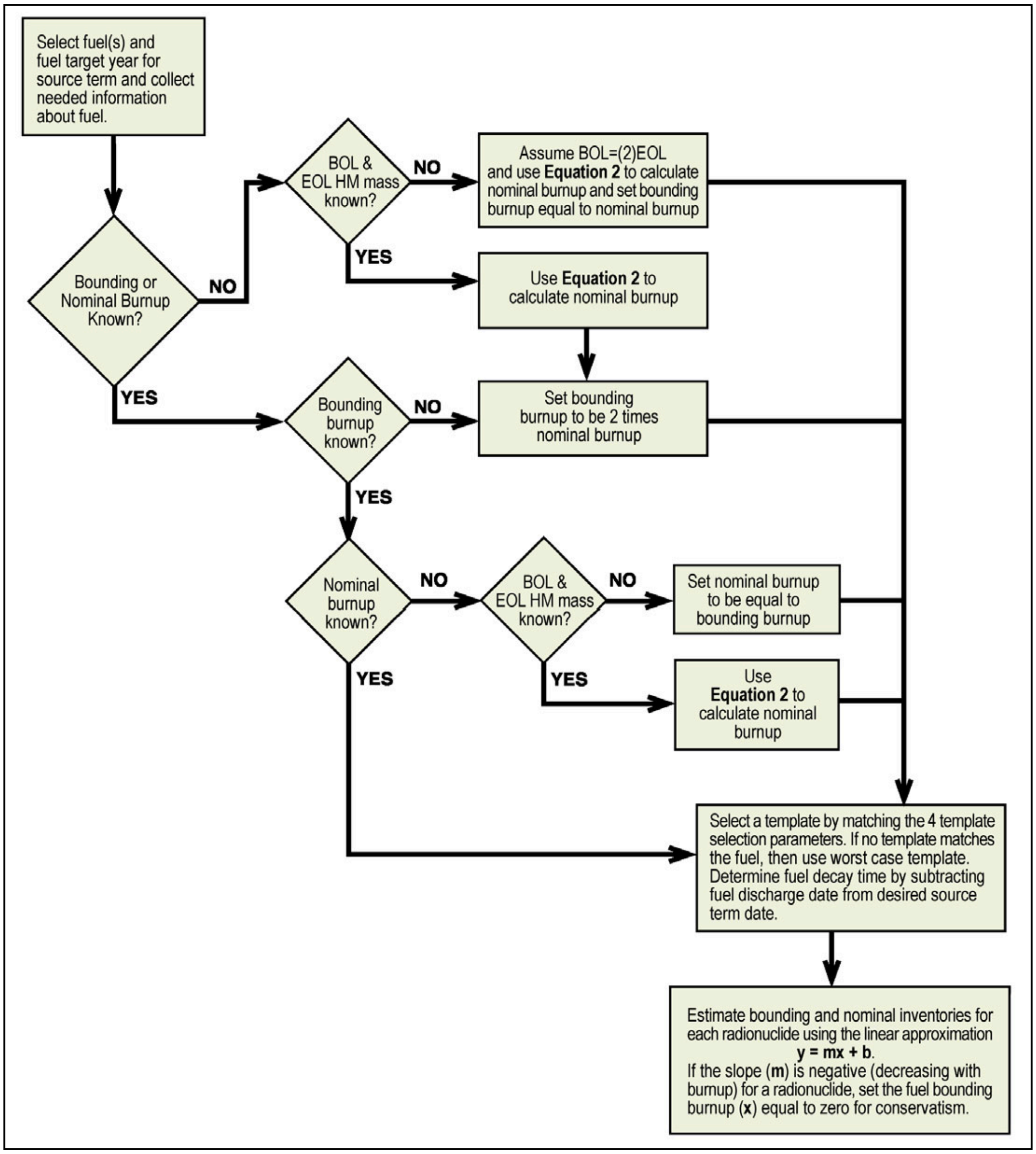

Figure 2. Logic flow diagram for determining radionuclide source term.

Equation 2 referenced in Figure 2 is shown below.

$$Burnup_{fuel} = (BOL_{fuel} - EOL_{fuel})\frac{(Burnup_{temp})}{(BOL_{temp} - EOL_{temp})} \qquad (2)$$

where the subscripts "fuel" and "temp" denote respectively, fuel being estimated and the template, and

BOL = beginning of life heavy metal mass (kg)
EOL = end of life heavy metal mass (kg)

If burnup data, and the BOL and EOL heavy metal masses are available for a particular spent fuel, the nominal burnup is calculated (using Equation 2) and compared to the given value. For conservatism, the higher of these two values is used.

The initial inventory, b_i, is presumed to be zero for all radionuclides except those present in the fresh fuel (e.g., U-235 for a uranium fuel). If needed, b_i is calculated using the enrichment and BOL heavy metal or by scaling the template BOL inventory to the mass of the fuel being estimated.

V. RESULTS

Implementation of the methodology has been automated and used to produce a radionuclide estimate for all DOE SNFs intended for repository disposition. Estimates include both the nominal and the bounding radionuclide inventories along with the associated heat generation rates and photon emission spectra. Inputs used for selecting and identifying the appropriate scaling factors were taken from the NSNFP Spent Fuel Database (SFD).

For each fuel, the results of the estimate are presented on a Fuel Radionuclide Inventory Worksheet (see Figure 3). Reference 8 provides Fuel Radionuclide Inventory Worksheets for each of 568 fuel records in the SFD, at the years 2010 and 2030. These dates, respectively, represent the estimated timeframes for packaging and shipment of fuels to the repository and for completion of emplacement of fuels in the repository.

To facilitate checking and assessment of the potential uncertainty, the worksheet displays all input used in the estimate, including any assumptions that were necessary in order to compensate for lack of fuel information. Each Fuel Radionuclide Inventory Worksheet contains three sections. Section I includes header information that identifies and provides key information for both the fuel being estimated and the template used in the estimate.

Section II shows the factors used in the linear estimate. Although estimates are performed for each of the 145 radionuclides in the selected template, the Fuel Radionuclide Inventory Worksheet displays only those identified as important for repository analyses (see Table 5 in Reference 8). The sum of the curies from the remaining radionuclides is also displayed on the Fuel Radionuclide Inventory Worksheet. The heat generation and photon emission rates associated with the estimated radiological inventory are also displayed in Section II.

Section III provides information to aid the analyst in assessing the suitability of the estimate. It includes subsections for Template Selection Summary, Burnup Summary, and Checks. The Template Selection Summary subsection provides a table that identifies the template selection parameters for the fuel being estimated and those of the template. A basis is provided to explain any of the parameters that do not match.

The Burnup Summary subsection provides a table that identifies the burnup values in the SFD, if available, and those estimated using the process shown in Figure 2. The table also provides a basis that documents the source (SFD or estimated) for the burnup value used in the estimate.

The Checks subsection provides the burnup multiplier and, when possible, the ratios of the estimated (i.e., calculated nominal and bounding) burnups and the estimated EOL heavy metal mass with those provided from the SFD.

The burnup multiplier is the ratio of the specific burnup (i.e., burnup per MTIHM) of the fuel being estimated over the specific burnup of the template fuel. For example, a burnup multiplier of 1 indicates that any scaling accounts for a different fuel mass only. No error is introduced when scaling only to account for different masses of fuel. Error is introduced, however, when scaling to account for different specific burnups. The burnup multiplier provides an indication of both the magnitude and the direction of the potential error associated with this linear approximation. As illustrated in Figure 1, the magnitude of this error is a function of both the nonlinearity of the buildup of each radionuclide with respect to burnup and of the magnitude of the scaling factor. The direction of this error is determined by whether the curvature of the radionuclide buildup is positive or negative and whether the burnup multiplier is more or less than one.

When the burnup values are available from the SFD and the heavy metal masses at BOL and EOL are also available to calculate the nominal burnup, the ratios of the given and calculated values are displayed. This ratio gives an indication of the integrity of the SFD input data.

Similarly, the heavy metal mass in the estimated radionuclide inventory is summed and compared to the EOL heavy metal mass given in the SFD. The ratio between the estimated and the given EOL heavy metal mass of the fuel is another cross-check that may alert the analyst of potential uncertainty associated with the data or the estimate. SFD EOL heavy metal values have been cross-checked against Nuclear Materials Safeguards and Security records and Material Control and Accountability records. A deviation in this heavy metal mass ratio is an indication that the heavy metal loadings of the template are not consistent with those of the fuel.

Figure 4 illustrates the quantity of DOE SNF and the associated radiological inventories relative to the assumptions that were necessary to compensate for unavailable fuel information. Each of the conservative assumptions used to compensate for insufficient information adds a degree of conservatism. Figure 5 clearly shows an inverse correlation between the available information used in the methodology and the resulting radionuclide concentrations (Ci/MTHM) estimated and provides evidence that the assumptions employed within the methodology are indeed conservative.

VI. DISCUSSION

The template methodology uses available information, conservative assumptions, and similarity principles to estimate radiological inventories for virtually any SNF for decay dates up to 100 years following reactor shutdown. This approach represents an effective method for obtaining reasonable and conservative source term estimates for those fuels that, by similarity, can be adequately modeled by another fuel for which depletion calculations are available. A spreadsheet application has been developed to apply the methodology to rapidly and economically estimate radionuclide inventories and the associated thermal heat generation and photon emission rates for a broad range of SNFs.

Fuel Radionuclide Inventory Worksheet

I. Fuel and Template Information

Fuel Name:	TRIGA FFCR	**[1]Fuel decay start date:**	1959
SNF ID #:	941	**Estimates as of:**	2030
Fuel Units & Descr:	3 - ELEMENT	**Template:**	TRIGA-SS (LW/U-Zrx, SST, 10 to 20%, U)
Heavy Metal Mass:	BOL=.47kg ; EOL=.46kg	**[2]Template Burnup(MWd):**	6.65
ROD Storage Site:	INEEL	**Template BOL Heavy Metal Mass (MT):**	0.000195
		Template Decay Time:	65 years

Estimated Canister usage
18"x10'
0.04

II. Estimates

Radionuclide	m Ci/MWd From Template	x_n Nominal Fuel Burnup (MWd)[2]	x_b Bounding Fuel Burnup (MWd)[2]	b Initial Activity (Ci)	y_n Nominal Fuel Inventories(Ci)	y_b Bounding Fuel Inventories(Ci)
Ac-227	1.2442E-08	16.138	32.276	0.00E+00	2.01E-07	4.02E-07
Am-241	4.0120E-03	16.138	32.276	0.00E+00	6.47E-02	1.29E-01
Am-242m	1.0749E-06	16.138	32.276	0.00E+00	1.73E-05	3.47E-05
Am-243	1.4692E-07	16.138	32.276	0.00E+00	2.37E-06	4.74E-06
C-14	1.2777E-04	16.138	32.276	0.00E+00	2.06E-03	4.12E-03
Cl-36	2.8120E-06	16.138	32.276	0.00E+00	4.54E-05	9.08E-05
Cm-243	4.1759E-08	16.138	32.276	0.00E+00	6.74E-07	1.35E-06
Cm-244	1.7098E-07	16.138	32.276	0.00E+00	2.76E-06	5.52E-06
Co-60	4.8241E-04	16.138	32.276	0.00E+00	7.79E-03	1.56E-02
Cs-134	1.5970E-10	16.138	32.276	0.00E+00	2.58E-09	5.15E-09
Cs-135	3.2195E-05	16.138	32.276	0.00E+00	5.20E-04	1.04E-03
Cs-137	6.8977E-01	16.138	32.276	0.00E+00	1.11E+01	2.23E+01
Eu-154	1.2238E-04	16.138	32.276	0.00E+00	1.97E-03	3.95E-03
Eu-155	6.7158E-06	16.138	32.276	0.00E+00	1.08E-04	2.17E-04
Fe-55	8.8165E-08	16.138	32.276	0.00E+00	1.42E-06	2.85E-06
H-3	3.8376E-04	16.138	32.276	0.00E+00	6.19E-03	1.24E-02
I-129	7.3684E-07	16.138	32.276	0.00E+00	1.19E-05	2.38E-05
Kr-85	5.2316E-03	16.138	32.276	0.00E+00	8.44E-02	1.69E-01
Np-237	1.3232E-06	16.138	32.276	0.00E+00	2.14E-05	4.27E-05
Pa-231	1.8722E-08	16.138	32.276	0.00E+00	3.02E-07	6.04E-07
Pb-210	1.2620E-12	16.138	32.276	0.00E+00	2.04E-11	4.07E-11
Pm-147	2.7714E-07	16.138	32.276	0.00E+00	4.47E-06	8.95E-06
Pu-238	6.4707E-04	16.138	32.276	0.00E+00	1.04E-02	2.09E-02
Pu-239	5.5203E-03	16.138	32.276	0.00E+00	8.91E-02	1.78E-01
Pu-240	2.1143E-03	16.138	32.276	0.00E+00	3.41E-02	6.82E-02
Pu-241	5.6872E-03	16.138	32.276	0.00E+00	9.18E-02	1.84E-01
Pu-242	2.3128E-07	16.138	32.276	0.00E+00	3.73E-06	7.46E-06
Ra-226	2.6466E-12	16.138	32.276	0.00E+00	4.27E-11	8.54E-11
Ra-228	2.5278E-10	16.138	32.276	0.00E+00	4.08E-09	8.16E-09
Ru-106	1.1377E-19	16.138	32.276	0.00E+00	1.84E-18	3.67E-18
Se-79	1.3009E-05	16.138	32.276	0.00E+00	2.10E-04	4.20E-04
Sn-126	1.2162E-05	16.138	32.276	0.00E+00	1.96E-04	3.93E-04
Sr-90	6.2511E-01	16.138	32.276	0.00E+00	1.01E+01	2.02E+01
Tc-99	4.4241E-04	16.138	32.276	0.00E+00	7.14E-03	1.43E-02
Th-229	9.4105E-10	16.138	32.276	0.00E+00	1.52E-08	3.04E-08
Th-230	1.7098E-10	16.138	32.276	0.00E+00	2.76E-09	5.52E-09
Th-232	2.5278E-10	16.138	32.276	0.00E+00	4.08E-09	8.16E-09
Tl-208	1.0305E-08	16.138	32.276	0.00E+00	1.66E-07	3.33E-07
U-232	2.7669E-08	16.138	32.276	0.00E+00	4.47E-07	8.93E-07
U-233	1.2239E-07	16.138	32.276	0.00E+00	1.98E-06	3.95E-06
U-234	3.1278E-07	16.138	32.276	0.00E+00	5.05E-06	1.01E-05
U-235	-2.6179E-06	16.138	0.000	2.03E-04	1.61E-04	2.03E-04
U-236	1.2696E-05	16.138	32.276	0.00E+00	2.05E-04	4.10E-04
U-238	-3.6331E-08	16.138	0.000	1.27E-04	1.27E-04	1.27E-04
Y-90	6.2541E-01	16.138	32.276	0.00E+00	1.01E+01	2.02E+01
Other Radionuclides					1.14E+01	2.29E+01

Gamma Sources

Photon Energy Group	Total Photons/sec (bounding)
Avg. MeV	
0.0150	1.104E+12
0.0250	2.291E+11
0.0375	1.999E+11
0.0575	2.153E+11
0.0850	1.290E+11
0.1250	8.366E+10
0.2250	1.111E+11
0.3750	4.847E+10
0.5750	8.280E+11
0.8500	7.964E+09
1.2500	3.863E+09
1.7500	2.050E+08
2.2500	2.845E+04
2.7500	1.174E+04
3.5000	3.988E+01
5.0000	1.679E+01
7.0000	1.895E+00
11.0000	2.154E-01

Thermal Power

Nominal Heat Output (Watts)	Bounding Heat Output (Watts)
1.28E-01	**2.56E-01**
Total	Total

III. Template Selection Summary, Burnup Summary, and Checks

Template Selection Summary

	From SFD	Used
Reactor Moderator:	LW AND U ZIRC HYDRIDE	LW AND U ZIRC HYDRIDE
Fuel Cladding:	SST (304)	SST
BOL HM Constituents:	U-ZrHX	U
BOL Enrichment %:	19.87312476	10 to 20

Basis for Parameter Differences:

Burnup Summary (MWd)[2]

	From SFD	Estimated	Basis for burnup used in estimate:
Nominal:	16.138	15.465	Nominal burnup taken directly from SFD (converted to MWd).
Bounding:		32.276	Bounding burnup assumed to be twice nominal burnup.

Checks

	Burnup Multiplier	Estimated Burnup/ Given Burnup
Nominal:	1.00	0.96
Bounding:	2.00	

Estimated EOL HM/Given EOL HM: 1.00

[1]Reactor shutdown, core removal, storage, shipping or other date confirming that irradiation ceased for fuel.

[2]Total burnup for all fuel associated with this worksheet must be divided by BOL heavy metal mass to get specific burnup values (MWd/MT).

Figure 3. Typical fuel radionuclide inventory worksheet.

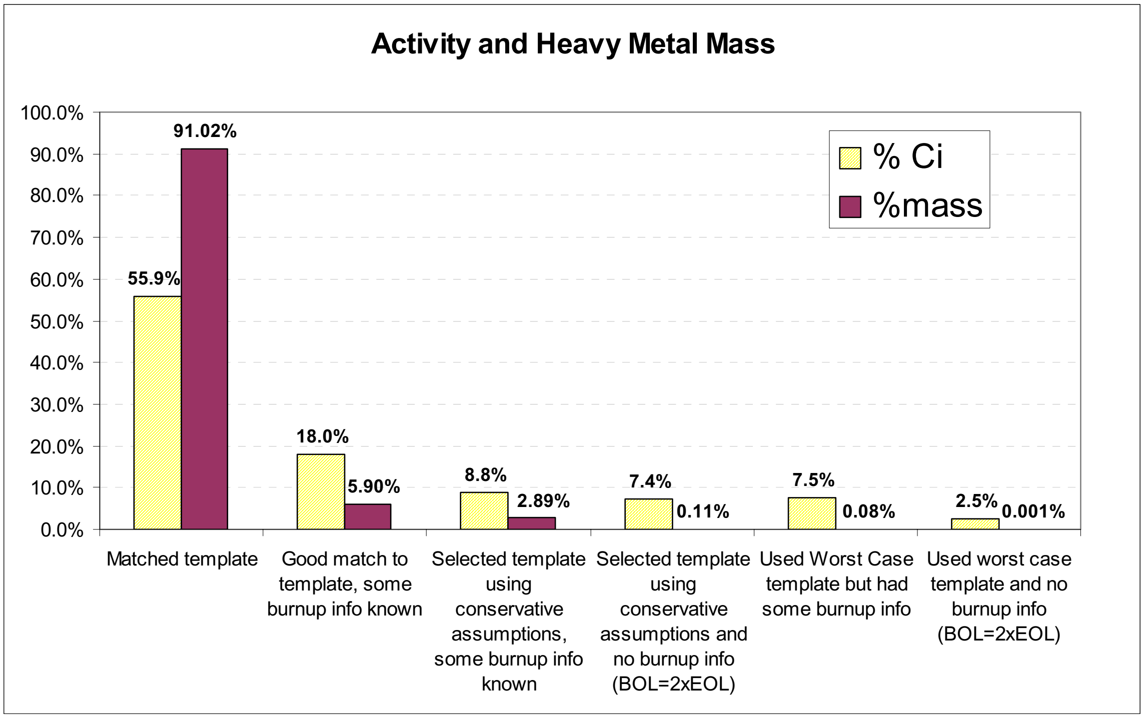

Figure 4. Activity and quantity of SNF relative to known information about SNF.

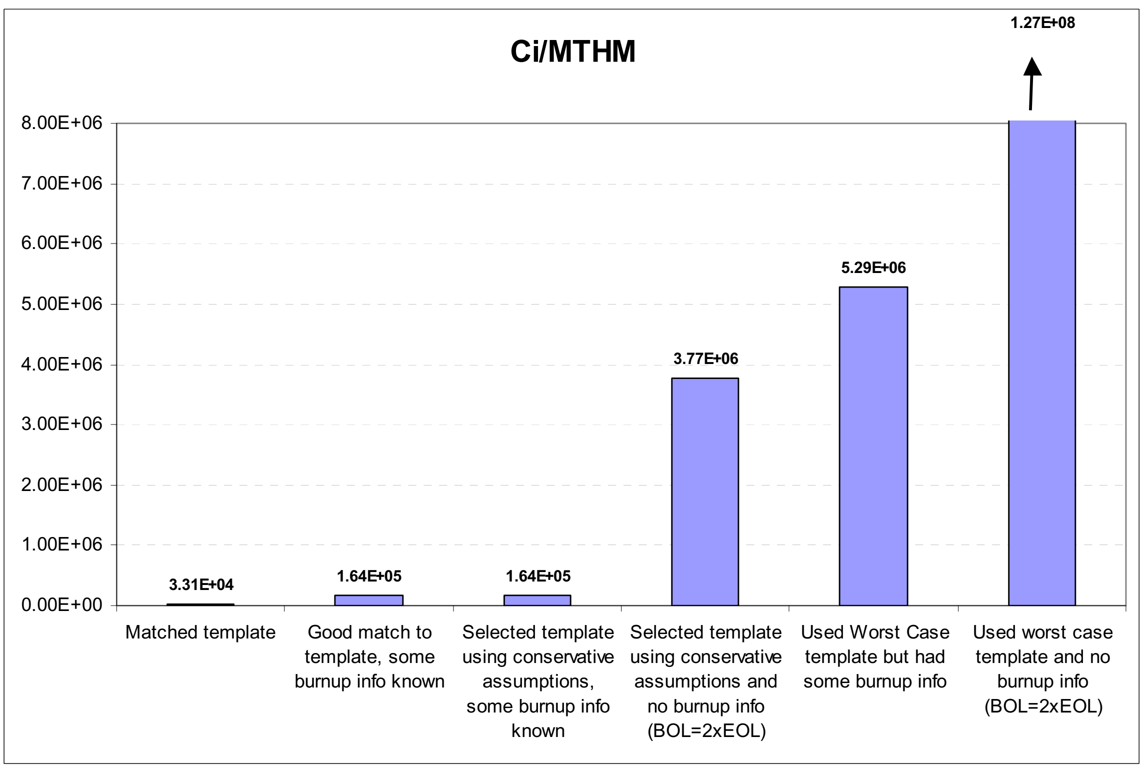

Figure 5. Activity per MTHM relative to known information about SNF.

The template methodology's inability to account for variations in spatial and neutron spectral properties and other higher order effects prevent one from assigning a definitive uncertainty to the final estimated radionuclide inventory. Uncertainty is addressed primarily by selecting and scaling the template to provide a high degree of confidence that the resulting estimate will be conservative. The methodology's suitability for use is thus limited to applications where the margin for error is sufficient to accommodate this conservative bias along with the uncertainty associated with the methodology.

The methodology has been used to estimate radionuclide inventories to support repository disposal for several hundred DOE SNFs. Reference 8 provides the results along with the inputs, assumptions, and calculations used in the estimates and a more comprehensive discussion of the sources of uncertainty.

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